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Fusion Engineering Design

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Design update of the ITER Upper Wide Angle Viewing System

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One of the diagnostic systems being provided by the US is the Upper Wide Angle Viewing System (UWAVS) which provides real-time, simultaneous visible and infrared images of the ITER divertor regions via optical systems located in five upper ports. UWAVS is designed in three main sections: in-vessel, interspace and port cell assemblies. Each assembly utilizes multiple steering and relay mirrors to direct the in-vessel light out of the tokamak to the port cell camera sensors. The primary design challenge of the in-vessel assembly is maximizing performance of the overall system while surviving the severe electromagnetic and nuclear ITER environment. A first mirror material study was conducted and determined that single crystal molybdenum was the best choice for the first two mirrors in the optical train. A fail open, bellows actuated shutter with cross pivot flexure design was determined to be the most reliable mechanism to protect the first mirror. A geometrically representative glow discharge mirror cleaning system is being designed and will be tested to maximize cleaning effectiveness while minimizing optical degradation of the molybdenum mirrors adjacent to the plasma. The shutter and first mirror assemblies were packaged and designed for replacement via remote handling methods to minimize radiation waste and cost associated with eventual component replacement. The preliminary optical and structural design provides a robust and reliable system while maximizing the field of view. The R&D efforts, the technical challenges and issues, and the design and analysis results are presented.

Keywords: ITER; WAVS; R&D; upper port; diagnostics

1. Introduction

Current preliminary design review (PDR) level efforts for the UWAVS program have focused on optical system design and analysis, R&D, and in-vessel system design and analysis. Key efforts for maturing these aspects of the design are discussed.

Text

The primary role of the UWAVS is machine protection via real-time, simultaneous visible and infrared images of the ITER wall and divertor regions at high spatial resolution (3-5mm) and frame rates (500-1000Hz). Temperature measurements of these regions are achieved using a two color approach. As much as 65% of the divertor regions are required to be imaged at one time using all five systems located in upper ports #2, 8, 11, 14, and 17. The combined coverage from the five systems can also aid in physics based measurements and secondary monitoring of the tokamak.

A modular approach is employed for the system to aid in assembly, alignment, testing and installation. Components of each region (fig. 1) will be assembled, aligned and acceptance tested prior to installation in ITER. Fiducials are expected in each port region to provide absolute and relative alignment of the subassembly via laser alignment. Broadband IR sources and temperature probes are used for in-situ calibration and optical performance monitoring.

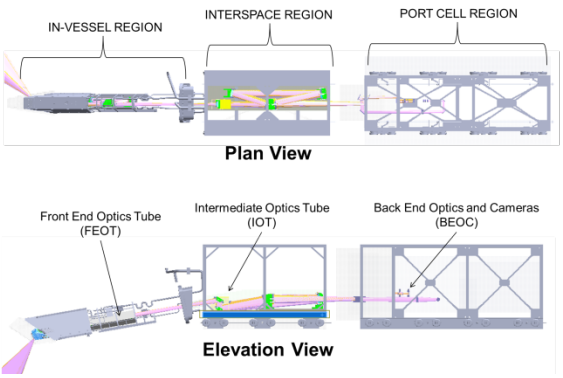

Fig. 1 Representative system layout in an upper port.

2. Design

Design of the in-vessel components to meet system level requirements is complicated by the harsh nuclear and electromagnetic ITER environment, along with the scarcity of design input parameters. Solutions to these challenges are addressed in this preliminary design phase.

2.1 Research and Development

The need for research and development of three key areas was identified early in the program for UWAVS: first mirror materials, mirror cleaning, and shutter design. Early efforts in these areas resulted in increased maturity of design parameters and reduced risk to the program.

A first mirror material study was completed, evaluating molybdenum, tungsten, stainless steel, copper and rhodium as candidate first mirror materials in UWAVS [1]. The choice of single crystal molybdenum (Sc-Mo) provides the highest opportunity for success based on the relatively high technical readiness level of the associated construction technologies, low sputtering

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yield, high specular reflectivity after sputtering, high thermal conductivity, low thermal expansion coefficient and low chemical activity. Metal coatings considered competitive to Sc-Mo are rhodium and multicrystal molybdenum, though substrate choice and manufacturing at this size reduces the technology readiness level of the overall mirror assembly.

Contamination of the first mirrors during plasma operations is expected and warrants the need for a mirror cleaning system. The mirror test cleaning setup (fig. 2) was designed and constructed to quantify optimal cleaning discharge parameters for effective and efficient cleaning of mirror surfaces in an ITER-like environment.

The irregular geometry of the inner test chamber simulates the internal geometry of the in-vessel housing of the first two mirrors of the optical train, i.e. two mirrors closest to the plasma inside the front end optics tube (FEOT). Test coupons of single crystal molybdenum (20x20x2mm thick) were procured and arranged in a lattice to simulate a full size (300mm dia) first mirror.

Fig. 2 Mirror cleaning test setup showing the inner chamber which houses the molybdenum mirror mockup.

The test plan matrix is designed to test a wide range of conditions to determine a suitable balance between cleaning effectiveness and surface degradation, and provide useful system design parameters. Commissioning of the test setup is complete and stable cleaning plasma has been created.

A single shutter is envisioned for protecting the first mirrors from contaminants during non-operation. A shutter study was completed and a preliminary design for a normally open, fail open mechanism was created and analyzed. A bellows actuated, cross pivot, flexure design for shutter articulation provides the highest reliability in the ITER environment. The fully elastic cross pivot eliminates friction while the independent halves of the mechanism can each provide 100% coverage of the aperture for redundancy. Radiative cooling provides adequate thermal management of the components with active cooling of the integral aperture envisioned to mitigate IR induced optical noise.

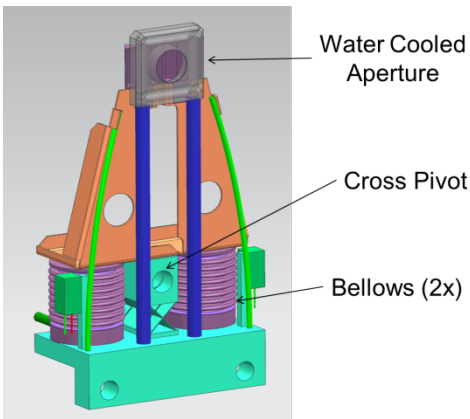

Fig. 3 CAD rendering of a preliminary shutter mechanism design in the closed position.

2.2 Optical Design

Collected light from the divertor is projected out of the vessel and through the interspace via steering and relay mirrors. Once the optical signal enters the port cell through a labyrinth in the bio-shield, it is split into a visible channel (400-730 nm) and two IR channels (fig. 4) used for two color measurement (3-3.5 um and 4-4.5um). These signals are focused onto camera sensors located in radiation and EM shielded compartments of the port cell.

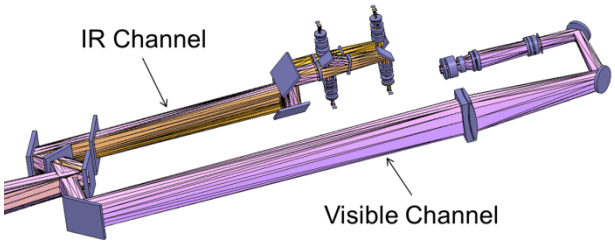

Fig. 4 Separations of the optical signal in the port cell region.

The interspace region contains a pair of active optics with a combined five degrees of freedom. These active optics primarily compensate for both radial and vertical motion between the in-vessel optics and out of vessel optics caused by thermal expansion of the vacuum vessel during operational and bake out conditions [2]. Additional range of motion is also provided to account for installation tolerances. Key design drivers for the remaining optical assemblies include EM and nuclear shielding, thermal stability, alignment, installation and space limitations. The camera sensors are located near the centerline of the port cell to maximize nuclear shielding thickness.

2.3 FEOT Design

The FEOT is a pinned and fastened assembly (fig. 5), primarily made of stainless steel components, and attached to the diagnostic shield module (DSM) for in-vessel operation. The majority of the structure is made up of six long panels and three thick bulkheads that support five optical assemblies. The construction method of the FEOT provides accurate and dimensionally stable interfaces, along with ease of assembly and accessibility; welding is minimized to reduce distortion and associated costs.

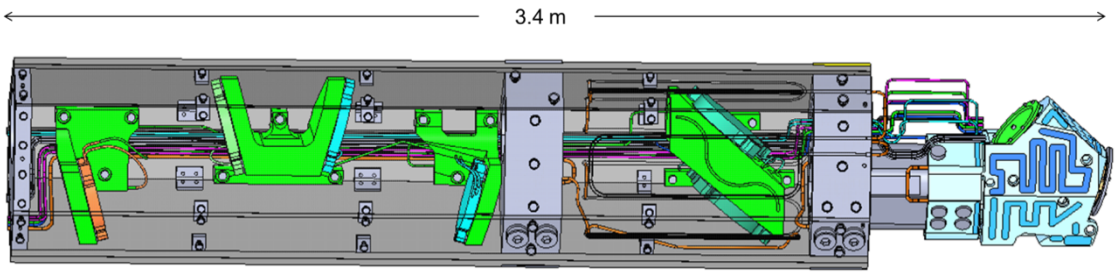

Fig. 5. FEOT assembly showing overall construction and internal components (some panels transparent for clarity).

Neutron streaming in the FEOT is mitigated by the labyrinth-like optical path consisting of thick stainless steel bulkheads and optical mounts. While more shielding and dog-legs were originally anticipated due to the material removed for the optical path, neutronic analysis results of the port plug assembly showed the majority of streaming stemmed from assembly tolerances and gaps around the DSM and other non-UWAVS interfaces.

Cooling channels throughout most of the optical components and support structures provide active thermal management for survivability and thermal stability. The exponentially decaying, nuclear heat load allows for passive cooling of structural components just beyond the forward bay volume of the FEOT.

Constraining the FEOT within the DSM is complicated by the required installation gaps, alignment tolerances and thermal mismatch to the DSM. The constraint scheme uses a combination of fasteners, shim pads and mechanical rams for accurate and custom alignment within the DSM while accommodating thermally induced movement.

Both front and rear portions of the FEOT structure are cantilevered requiring a low mass and high stiffness structure to maintain optical alignment and combat low frequency bending modes. The initial design maximized outer envelope dimensions and internal volume, but optical component mass reduction is still foreseen to alleviate inertial loading.

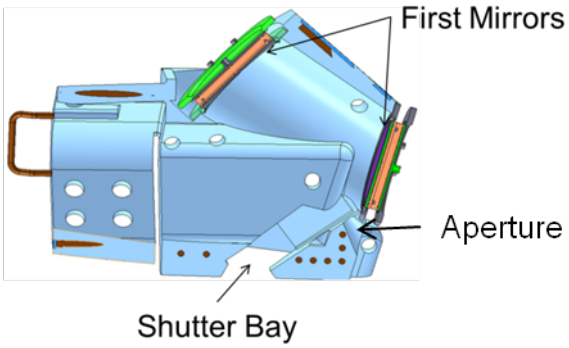

Fig. 6 Cross section of the A10 assembly showing locations of the first mirrors and shutter bay.

Tightly controlled interfaces are provided for the five optical assemblies supported by the FEOT to ensure accurate initial alignment. The forward most optical assembly of the FEOT is the A10 (fig. 6). It houses the first two mirrors, calibration sources, and shutter, and is designed to be replaceable using remote handling methods in the hot cell. The mount and interface design for this assembly is complicated by the combination of structural, thermal, remote handling and space envelope requirements. EM loads were especially dominant at the A10 interface. A socket type interface to the FEOT was chosen to best resist multi-axis, EM torque loads, and provide accessibility related to removal and installation of the A10 assembly via remote handling methods.

3. Analysis

Two analysis paths were needed to validate the UWAVS design during this phase of the program and are categorized by normal and upset load conditions [3][4]. Normal load deformations were exported for optical analysis and compared with performance requirements. Upset load deformations were evaluated per the Structural Design Criteria for ITER In-vessel Components (SDC-IC) guidelines to determine survivability; performance requirements can be neglected during upset loading conditions, and therefore ignored.

3.1 Multiphysics Analysis

A multiphysics approach was needed in order to fully characterize the various loads and assess the response of the FEOT for the two loading condition. The upset case is the design driving condition for the structure and includes loading from a plasma disruption, seismic event, nuclear heating, fastener preload and coolant line pressure.

Several design iterations of the thermal management scheme were completed in parallel with the structural analyses and evaluated using the ANSYS fluid analysis module, CFX. Analytical estimates of flow parameters were validated (fig. 7) and detailed design iterations of the cooling channel paths and geometry were matured. Results were imported into the static thermal model.

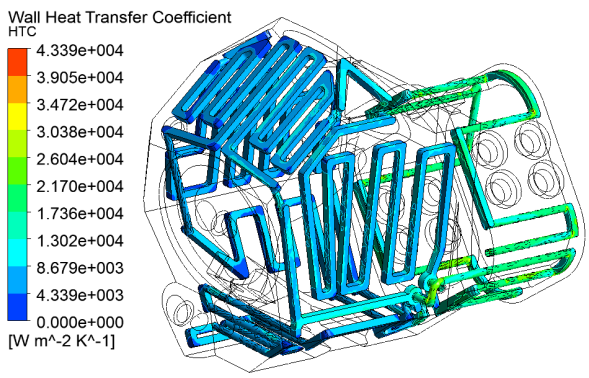

Fig. 7 Contour plot of wall heat transfer coefficient for the A10 structural coolant channels.

The FEOT temperature distribution during nominal operation was determined via static thermal analysis. Temperature targets for nominal operation are 35 C for optical components and range from 50 C to <200 C for structural components. Resulting temperatures (fig. 8) showed passive cooling is adequate for structures beyond the middle bulkhead. Structures closer to the

plasma required active cooling with maximum coolant channel spacing decreasing to a few centimeters nearest the plasma.

Fig. 8 Contour plot of FEOT temperatures from worst case nuclear heating

Several modal and static structural analyses were performed on the FEOT during design maturation. Even through mass and geometry optimization, the modal response of the cantilevered FEOT resulted in inertial accelerations above 100 m/s². This loading proved to be the most dominant and resulted in unacceptable bending stresses in panels and fasteners. Constraining the back end to the upper port plug structure is therefore favored to achieve positive structural margins.

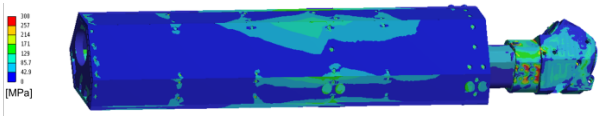

Fig. 9 Contour plot of FEOT stresses from upset loading

3.2 Optical Analysis

ZEMAX was used to aid in the optical system design optimization and conduct performance analysis. Effects of optical surface manufacturing tolerances, assembly and alignment tolerances, and thermal and inertial induced deformations during normal loading were evaluated and compared to the baseline system performance. Modulation transfer function (MTF) plots were created for the visible and IR wave bands under nominal operating conditions. Results show visible and IR spatial resolutions are close to or exceeding the required 30% at 5mm and 3mm resolution, respectively. Figure 10 shows the MTF for the 4-4.5 μm band and should be evaluated at 7.31 line pairs per mm for accurate performance at the true object plane.

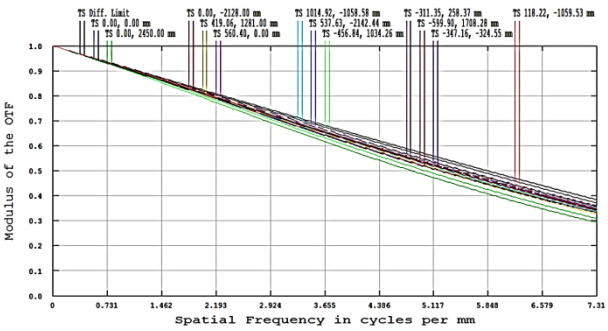

Fig. 9 MTF plot for the 4-4.5 μm band under nominal loading conditions and expected installation tolerances.

Lasnier et al [5], created math models to quantify optics-emitted IR power as a function of emissivity, wavelength, and optics temperature (fig. 11) for three different color bands. The two color bands selected for the UWAVS two color measurement are 3-3.5 μm and 4-4.5 μm. The 4.5-5 μm color band was determined to be undesirable due to high absorption and emission by the sapphire windows at the vacuum vessel closure plate. The ratio of intensities in the two selected color bands are corrected and used to determine divertor temperature for an uncertain divertor emissivity.

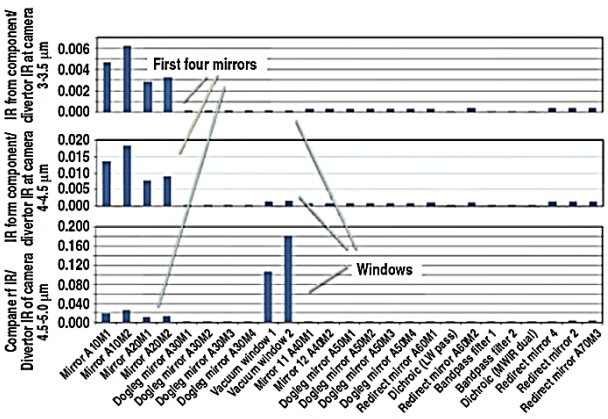

Fig. 11 IR contributions of each optical component relative to divertor signal (taken from ref 1).

4. Conclusions and Future Work

Several design challenges of the UWAVS have been addressed during the PDR phase of the program. Mirror cleaning test setup commissioning is complete and results from the full test campaign will provide needed system design parameters for the final design. The FEOT and associated optical system has been evaluated under nominal and upset load conditions, and further maturing of these systems is being planned. Interspace and port cell design efforts will continue through the 4th quarter of 2016. The UWAVS program is on track for PDR in the 4th quarter of 2017.

Acknowledgments

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[6] SRD for mtf?